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THE OUTSKRITS OF SPIRAL GALAXIES: EVIDENCE FOR MULTIPLE STELLAR POPULATIONS

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ABSTRACT

We present an analysis of the metallicity distribution functions of fields projected along the minor axis for a sample of inclined spiral galaxies in order to search for evidence of the presence of multiple stellar populations. In all cases, the stellar populations appear to have asymmetric metallicity distributions with very high confidence levels. The mean metallicities of both stellar subpopulations, determined from mixture modelling of the metallicity distribution functions, correlate with parent galaxy luminosity. This suggests that the vast majority of field stars have probably formed in galactic fragments that were already embedded in the dark matter halo of the final galaxy. The steeper correlation between the mean stellar metallicity and parent galaxy luminosity is driven by an increasing fraction of metal-rich stars with increasing galaxy luminosity. Metal-poor components show larger dispersion in metallicity than metal-rich components. These properties are in striking similarity with those of globular cluster subpopulations around early-type galaxies. The properties of field stars along the minor axis are consistent with a formation scenario in which the metal-poor stars formed in all galaxies, possibly as a result of tidal disruption of dwarf-like objects. An additional metal-rich component might be related to the formation of the bulge and/or the disk.

Subject headings: galaxies: halos – galaxies: stellar content – galaxies: individual (NGC 55, NGC 247, NGC 300, NGC 3031, NGC 253, NGC 4244, NGC 4945, NGC 4258)

1. INTRODUCTION

Stars in the outskirts of galaxies are among the oldest and the most metal-poor stellar components of galaxies. Therefore their properties are clues to the understanding of how galaxies have assembled their mass. Remarkably little is known about these populations in other spiral galaxies, and their formation histories. Recently, Mouhcine et al. (2005a,b) presented a study of the properties of stellar populations along the minor axis of a sample of highly inclined spiral galaxies beyond the Local Group. Their mean metallicities are found to correlate with parent galaxy luminosity, in the sense that bright galaxies tend to have more metal-rich stars than faint galaxies. The observed metallicity distribution functions show sharper cut-off at the metal-rich end, with an excess of intermediate metallicity stars in comparison to the simple chemical evolution model predictions. Interestingly, the stellar populations in the outskirts of early type galaxies have similar properties to those of spiral galaxies at a similar parent galaxy luminosity.

One of the most noteworthy fundamental findings in galaxy property studies is the bimodal nature of metallicity/color distributions of globular cluster systems of (early-type) galaxies (e.g., Peng et al. 2006 in references therein). A large body of evidence has established that the properties of globular cluster systems of early-type galaxies are linked to those of their host galaxies (e.g., van den Bergh 1975; Brodie & Huchra 1991; Forbes et al. 1997; Kundu & Whitmore 2001, Larsen et al. 2001). The globular cluster formation scenarios discussed to date predict all a link between metal-rich globular clusters and field stars (e.g., Ashman & Zepf 1992; Forbes et al. 1997; Strader et al. 2004). This is supported by observation of several globular cluster systems (e.g., M 31: Jablonka et al. 2000; NGC 5128: Harris & Harris 2002; NGC 1399: Forte et al. 2005), and the nearly constant *bulge specific frequency* in elliptical galaxies and spiral bulges (Forbes et al. 2001). Forte et al. (2005) have discussed the arguments to support the conclusion that field stars may show two major stellar populations that share the properties of each globular cluster subpopulation. For the particular case of the early-type galaxy NGC 1399, which exhibits a bimodal globular cluster metallicity distribution, the galaxy surface brightness profile, the color gradient and the behavior of the cumulative globular cluster specific frequency, are compatible with the presence of two dominant diffuse stellar populations, associated with blue and red globular cluster subpopulations (Forte et al. 2005). The reconstructed metallicity distribution function of field stars in the outskirts of NGC 1399 shows striking similarities with those of the outer fields of the early-type galaxy NGC 5128 (Harris & Harris 2000), and M 31 (Durrell et al. 2001, 2004), i.e., strongly weighted to moderately high metallicities with a metal-poor tail extending to [Fe/H] ~ -2.5.

The observed metallicity distribution function of NGC 5128 field stars is matched reasonably well by the predicted distribution of the accreting box chemical evolution model, as long as the star formation took place over an *extended period*, simultaneously with a rapid inflow of very metal-poor gas that declines exponentially with time (Harris & Harris 2002). However, there is *no* accreting box chemical evolution model that could reproduce the shape of the metallicity distribution function of the galaxy globular cluster system (Vandalfsen & Harris 2004). Using the accreting box chemical evolution models to reproduce the shapes of field star metallicity distribution functions,

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and mixture models to reproduce those of globular cluster systems, ignores the observational evidence supporting a likely connection between globular cluster systems and field stars. Interestingly, by fitting mixture models to the metallicity distributions of field stars in the outskirts of M 31 and NGC 5128, Durrell et al. (2001) and Harris & Harris (2000) have found that the metal-rich and metal-poor peak metallicities are similar to those of globular cluster systems of both galaxies. Note however that the metallicity distribution functions of field stars have significantly different shapes from those of globular cluster systems for both M 31 and NGC 5128. While field stellar populations are dominated by metal-rich stars, i.e., [Fe/H] ~ -0.5, with a metal-poor tail, far more globular clusters are metal-poor (see Harris & Harris 2002 and Forte et al. 2005 for a possible interpretation of the observed increase of the number of globular clusters per unit field star numbers at low metallicity).

Little is known about the globular cluster systems of spirals. Goodfrooij et al. (2003) have shown that their properties are consistent with a scenario in which globular cluster systems are made up of a *universal* halo population of globular clusters that is present around each galaxy, and a second population associated with the bulge, which grows approximately linearly with its mass (see also Chandar et al. 2004). However, a few spirals did not show evidence for systems of inner metal-rich globular clusters, consistent with a scenario of bulge formation through secular processes (see Olsen et al. 2004). By comparing the properties of globular cluster systems for a sample of spirals and early-type galaxies, Forbes et al. (2001) have concluded that the formation of globular cluster systems of both class of galaxies might share similarities. The observed similarities between the properties of field stars along the minor axis of bright spirals and those at the outer parts of early-type galaxies suggest that the conclusion of Forte et al. (2005), i.e., there is multiple diffuse stellar populations in the outer parts of early-type galaxies, could be extended to field stars in the outskirts of spirals. The aim of this paper is to look for further evidence for multiple stellar population along the minor axis using the approach used extensively for globular cluster systems, i.e., a fitting of mixture models to field star metallicity distribution functions constructed by Mouhcine et al. (2005c).

The layout of this paper is as follow; in § 2 we present briefly the data set. In § 3 we report correlations between the properties of the stellar populations in spiral galaxy outskirts and host galaxy luminosities. The implications of our finding for the formation and evolution of the stellar populations in the outer regions of galaxies are discussed in § 4.

2. GALAXY SAMPLE AND METALLICITY DISTRIBUTION FUNCTIONS

Mouhcine et al. (2005a,b,c) have observed a sample of spiral galaxies using the Wide Field Planetary Camera 2 on broad the Hubble Space Telescope with the aim of unambiguously resolving their stellar populations along the minor axes down to one or two magnitudes below the tip of the red giant branch. The galaxy selection criteria, observations, and the data reduction have been described in detail by Mouhcine et al. (2005c). We therefore only briefly summarize this information here. The sample consists of nearby inclined spirals located at high Galactic latitude, i.e., $|b| > 30°$, with morphological types from Sa to Sc. The observed fields locate well outside the visible outskirts of the disks and bulges on the Palomar Sky survey. Photometric errors and incompleteness were estimated over the color-magnitude diagram by using artificial star experiments. The depth of the observations vary from galaxy to galaxy, with 50% completeness limits ranging from red giant star absolute I-band magnitudes -0.9 to -3.5.

The sensitivity of photometric properties of red giant stars to metallicity rather than age offers an opportunity to derive first order metallicity distribution functions of stellar populations from photometric data. To derive the metallicity distribution functions for the galaxy sample, the locations of red giant stars in the color-magnitude diagrams were compared to their predicted location (e.g., Harris & Harris 2000; Sarajedini & Van Duyne 2001; Brooks et al. 2004; Tiede et al. 2004). A dense fiducial grid of theoretical red giant branch tracks from VandenBerg et al. (2000) on the M_I/(V-I) diagram has been superimposed on the foreground extinction-corrected data, and interpolate between them to derive an estimate of stellar metallicity on a star-by-star basis. All the models we used assume that the stars are $\alpha-$enhanced, i.e., $[\alpha/\mathrm{Fe}]$=0.3. To cover stars located beyond the most metal-rich track of the theoretical grid, we add the observed red giant branch fiducial of the old metal-rich disk open cluster NGC 6791 (Taylor 2001). To avoid biasing the derived metallicity distribution functions, stars that are one time the (V-I) color error bluer, at a given reddening-corrected I-band magnitude, than the lowest metallicity track, as well as for stars redder than the highest metallicity fiducial track, were included to construct the metallicity distribution functions. Their metallicities were estimated by extrapolating the relationship between the colors of fiducial tracks at a given reddening-corrected I-band magnitude and their metallicities. This leaves a very small number of stars out the sample considered for building the metallicity distribution functions. The color-magnitude diagrams of the observed fields are dominated by old red giant stars, with no clear evidence for the presence of an intermediate age stellar population component, i.e., younger than ~ 4 Gyr (see Mouhcine et al. 2005c). The error in assuming a ~ 12 Gyr age instead of a ~ 6 Gyr is that the metallicity is underestimated by 0.2-0.3 dex, of order the errors of the calibration used to estimate stellar metallicity from optical photometry.

For nearly all sample galaxies, apart from NGC 4258, the 50% completeness limit falls well below the brightest end of the red giant branch to allow accurate measurements of the metallicity distribution functions (see Fig. 2 and Fig. 3 of Mouhcine et al. 2005c). To account for the effects of incompleteness, each star was counted as the inverse of the photometric completeness at the location of the star on the color-magnitude diagram. For NGC 4258, the photometry does not probe the red giant branch far, and the 50% completeness level limit falls close to the brightest end of the red giant branch sequence. We have limited ourselves to a range of I-band magnitudes where the completeness level is not severely low,

i.e., higher than 50%. However, stars with metallicities higher than [Fe/H] ~ -0.7 lie at fainter magnitudes than the magnitude range chosen to construct the metallicity distribution function of stars at the outskirts of NGC 4258. For this galaxy, the metal-rich end of the metallicity distribution function is suspected to be incomplete, i.e., a fraction of metal-rich stars are missing.

3. RESULTS FOR METALLICITY DISTRIBUTION FUNCTIONS

The histograms shown in Fig. 1 represent the measured incompleteness-corrected metallicity distribution functions for all galaxies in the sample, ordered by decreasing luminosity. An optimal bin width was estimated on a case-by-case basis according to the star sample size and the distribution's skewness (Scott 1992). In each metallicity distribution a strong relatively metal-rich peak is prominent, and each distribution is asymmetric about this peak. The issue is to determine how strongly a two Gaussian fit is preferred at any level in the metallicity distribution functions over simpler models such as a Gaussian distribution. The properties of metallicity distribution are quantified using the widely used Kaye's Mixture Model (KMM) statistical test (Ashman, Bird, & Zepf 1994 and references therein). The KMM test uses the maximum likelihood technique to test if a distribution is better modelled as a sum of two Gaussian than as a single Gaussian (the null hypothesis). The p-value returned by KMM adequately measures the statistical significance of the improvement in the fit in going from one to two groups. As there is no reason to assume that both populations in the fit have similar dispersions, a mixture model fitting is applied to the data such that the dispersion for the two populations are not constrained to be identical, i.e., the so-called heteroscedastic fitting.

Ashman et al. (1994) have cautioned that the output likelihood in the case of heteroscedastic fitting is difficult to interpret, and propose to perform bootstrap simulations to assess the result of the fitting. We generate a large number of synthetic samples by randomly selecting stars with replacement from the original data set, constructing the metallicity distribution, and finally applying the KMM test to the simulated samples. The distributions of the mixture fit parameters for the synthetic samples are fitted by Gaussian, and then their means and dispersions are taken to be the final estimates of the mean value and the formal error for each fit parameter.

The parameters for the best fit models for the two peaks, referred to as the metal-poor and the metal-rich hereafter, as assigned by the KMM test are presented in Table 1. Fig. 1 shows the double Gaussian distributions corresponding to the metallicity peaks and their sum. The p-value is close to zero in all cases, indicating high probabilities that two Gaussian are better fits to the metallicity distribution functions than single ones. The uncertainties in distance modulus and the foreground extinction have rather small impact in all fitted parameters: less than 0.1-0.15 dex for the mean metallicities, 0.05 dex for the dispersion, and a few percent for the fraction of stars in each stellar component, with the overall shape of the metallicity distribution unchanged.

Using the mixture model estimates, we can investigate the behavior of metal-rich and metal-poor stellar populations as a function of host galaxy luminosity. An obvious question is whether a stellar metallicity vs. galaxy luminosity relation and/or other correlations are present for both subcomponents, as for both blue/metal-poor and red/metal-rich globular clusters of early-type galaxies. An important question is to know whether the stellar luminosity-metallicity relation reported by Mouhcine et al. (2005a) might result from different mixture of two populations with roughly constant metallicities. We have augmented our database with similar published measurements for the stellar populations in the outskirts of M 31 (Durrell et al. 2001), and the giant E/S0 NGC 5128 (Harris & Harris 2000).

The left panel of Fig. 2 shows the relationships between mean metallicities of the stellar population subcomponents as returned by the KMM test, the mean metallicity of field stars as derived by Mouhcine et al. (2005b), and the host galaxy V-band luminosity. The metallicities of both metal-poor and metal-rich stellar population subcomponents in the outskirts of spirals clearly increase for brighter host galaxies. The slopes of the luminosity-metallicity correlations are similar for both stellar subcomponents. A consequence of this is a nearly constant offset between the metallicities of the two subcomponents across nearly three orders of magnitude in galaxy luminosity. The observed similarity suggests that the conditions of metal-rich and metal-poor star formation could not have been too different across a large range of host galaxy luminosity/mass. The metallicity-luminosity relation for the total resolved stellar populations is much steeper than those seen for both subpopulations. This suggests that the increasing metallicity of the stellar populations in the outer regions for brighter host galaxies is due to an increasing contribution of metal-rich stars.

The right panel of Fig. 2 shows the variation of the fitted metallicity dispersion for the stellar subpopulations as a function of parent galaxy luminosity. The metallicity dispersion of metal-poor subpopulations correlates with galaxy luminosity, i.e., brighter galaxies tend to have metal-poor subpopulations with larger metallicity dispersions than faint galaxies. However, the metallicity dispersions of metal-rich subpopulations lack any correlation with galaxy luminosity, and scatter around the mean metallicity dispersion of ~ 0.25, smaller than the metallicity dispersion of metal-poor stellar subpopulations.

The properties of the stellar populations in the outskirts of M 31, and more interestingly NGC 5128, agree nicely with the correlations defined by our galaxy sample. This suggests that the formation of field stars in the outer regions of early-type galaxies might share similarities with those in the outer regions of spirals, in agreement with the conclusion of Forbes et al. (2001) regarding globular cluster systems. This supports the idea that the diffuse stellar populations in the outer regions of galaxies exhibit a dual nature reflecting the presence of two major stellar populations that share the properties of each globular cluster subpopulations (see Forte et al. 2005).

4. IMPLICATIONS FOR THE FORMATION OF THE OUTSKIRTS OF SPIRALS

We have thus found that the properties of field stars in the outer regions of spirals are correlated with parent galaxy luminosity. Given these correlations, what may be the nature of the diffuse stellar populations in the outskirts of spiral galaxies? The correlations of mean metallicities of both subcomponents with galaxy luminosity indicate that the formation of both metal-rich and metal-poor stellar populations is linked to their host galaxies.

These constraints fit well into the *in situ* scenario in which at least a significant fraction of field stars in the outer regions of spiral galaxies has been formed after the parent galaxies assembled into individual entities. The similar range of metallicities covered by metal-poor stars and the Local Group dwarf galaxies indicates that metal-poor stellar populations may be built up by the disruption of protogalactic fragments with sizes similar to those of the present-day Local Group dwarf galaxies. This does not imply however that the disrupted galactic fragments have stellar formation histories similar to those of dwarf galaxies in the Local Group (see e.g., Shetrone et al. 2003, Venn et al. 2004 for a similar conclusion regarding the formation of the Galaxy stellar halo). The chemical properties of stars in the outer regions of spirals beyond the Local Group are not available yet to constrain the details of their star formation histories. The correlation of the mean metallicities of metal-poor field stars with the host galaxy luminosity suggests that the disrupted fragments were already embedded in the dark matter halo of the final galaxy after its assembly rather than being independent satellites.

The mean metallicities of metal-rich subcomponents suggest that they formed in protogalactic fragments that are more massive, and thus more evolved chemically, than progenitors of present-day dwarf galaxies in the Local Group. The correlation of mean metallicities of metal-rich components with galaxy luminosity indicates that metal-rich stars knew about the size of the final galaxy to which they belong.

A metallicity dispersion could be the result of star formation events where stars form over a period of time long enough to produce different generations of stars with different chemical abundances, or also by the merging of different stellar systems that were chemically isolated from each other, whether spatially or temporally (see Peng et al. 2006). The latter scenario could apply to the metal-poor component in the outskirts of spirals formed from the disruption of isolated fragments. The metallicity dispersion of dwarfs in the Local Group does not depend on galaxy luminosity (see Côté et al. 2000 for more details). The metallicity dispersion of a disrupted population of fragments with sizes similar to those of present-day dwarfs is expected to increase with the host galaxy luminosity/mass. The narrower metallicity dispersion of metal-rich components, especially for bright galaxies, indicates that the metal-rich stars may be formed in few large star formation events where the gas is well mixed. The lack of a correlation between the metallicity dispersion of metal-rich subcomponents and galaxy luminosity suggests that these star formation events were possibly uncorrelated with the assembly of galactic disks, which dominate the light budget in present-day intermediate and late-type spiral galaxies.

One of the most pressing questions regarding spiral galaxy evolution is the connection between globular cluster systems and field stars. The disruption of globular clusters, revealed by tidal tails (e.g., Grillmair et al. 1995), may contribute to the formation of the stellar component at the outskirts of galaxies (Aguilar et al. 1988; see Freeman & Bland-Hawthorn 2002 for a detailed discussion). Our knowledge of globular cluster systems in spiral galaxies is still limited to a handful of galaxies (e.g., Harris 1991; Ashman & Zepf 1998; Rhode & Zepf 2003). A view is emerging however that inner metal-rich globular clusters in spiral galaxies may be associated with their bulges (Minnitti 1995; Côté 1999; Barmby et al. 2001; Perrett et al. 2002; Forbes et al. 2001; Goudfrooij et al. 2003). Stars belonging to the metal-rich component could be identified as field stars associated with the formation of metal-rich globular clusters. If this is indeed how the metal-rich components form, one would expect their mean metallicities to vary systematically along the Hubble sequence of spirals, and metal-rich stars in the outskirts of spirals to show kinematics similar to bulge stars. The strong rotation of both globular clusters and field stars in the inner speroid of M 31 (Perrett et al. 2002; Hurley-Keller et al. 2004), as well as in the outer halos of some giant ellipticals (Côté et al. 2003, Peng et al. 2004) support the existence of a connection between metal-rich field stars and metal-rich globular globular clusters. For M 31, Ibata et al. (2005) have argued however that the rotating structure is related to an extended disk rather than to the bulge.

The formation scenario of field star populations in the outskirts of spirals discussed here shares similarities with the scenarii proposed by Forbes et al. (1997) and Rhode & Zepf (2004) to account for the observed properties of globular cluster systems of early-type galaxies. Peng et al. (2006) have conducted a homogeneous study of globular cluster systems of a large sample of early-type galaxies in the Virgo cluster. The observed overall behavior of globular cluster systems, i.e., the correlation of both subpopulation mean metallicities with galaxy luminosity, the correlation of metallicity dispersion of metal-poor globular clusters with galaxy luminosity, and the lack of a correlation between galaxy luminosity and metallicity dispersion of metal-rich globular clusters, are similar to what is established here for field stars in the outskirts of spirals. This suggests that the formation histories of the stellar populations in the outer regions of both early-type galaxies and spirals might have features in common. However, the details of the scaling relations are different. The subcomponents of globular cluster systems of early-type galaxies show shallower luminosity-metallicity relations, and larger metallicity dispersions than those of field stars populations in the outskirts of spirals. The implications of those differences on the understanding of the assembly histories of stellar populations in the outer regions of galaxies are not clear due to the small number of galaxies in our sample, which affect the determination of the slopes of the luminosity-metallicity relations of field star subcomponents, and the uncertainties affecting the determination of the absolute globular cluster metallicities from braod band colors (see Peng et al. 2006 for a detailed discussion of this issue).

The formation scenario of the outer regions of spiral galaxies that emerges here is, as yet, only an approxima-

tive (and speculative) outline. Given the importance of this issue in the context of our understanding of the formation of galaxies, more data are needed to investigate the variation of chemical abundances, kinematical properties, and spatial distributions of field stars in the outer regions of galaxies over large fields, dependence on galaxy morphological type etc, in order to test the observational consequences of such a scenario.

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Table 1

Results of the KMM test applied to the metallicity distribution of the sample galaxies. Columns: (1) Galaxy name; (2) galaxy magnitude; (3) the statistical significance that the MDF is unimodal; (4) fraction of the metal-rich peak; (5) metallicity of the metal-rich peak; (6) spread of the metal-rich peak; (7) fraction of the metal-poor peak; (8) metallicity of the metal-poor peak; (9) spread of the metal-poor peak.

Galaxy	$M_{V,\circ}$	p	f_R	$[Fe/H]_R$	σ_R	f_P	$[Fe/H]_P$	σ_P
NGC 300	-18.62	0.004	0.459	-1.17	0.20	0.541	-1.89	0.20
NGC 247	-18.91	0.051	0.820	-0.96	0.30	0.180	-1.66	0.30
NGC 4244	-18.96	0.000	0.798	-1.05	0.29	0.202	-1.86	0.26
NGC 55	-19.02	0.006	0.752	-1.06	0.23	0.248	-1.78	0.24
NGC 4945	-20.77	0.000	0.799	-0.63	0.23	0.201	-1.16	0.42
NGC 253	-21.13	0.000	0.616	-0.64	0.22	0.384	-1.24	0.43
NGC 3031	-21.14	0.000	0.884	-0.83	0.34	0.116	-1.91	0.21
NGC 4258	-21.34	0.000	0.476	-0.68	0.13	0.524	-1.21	0.39

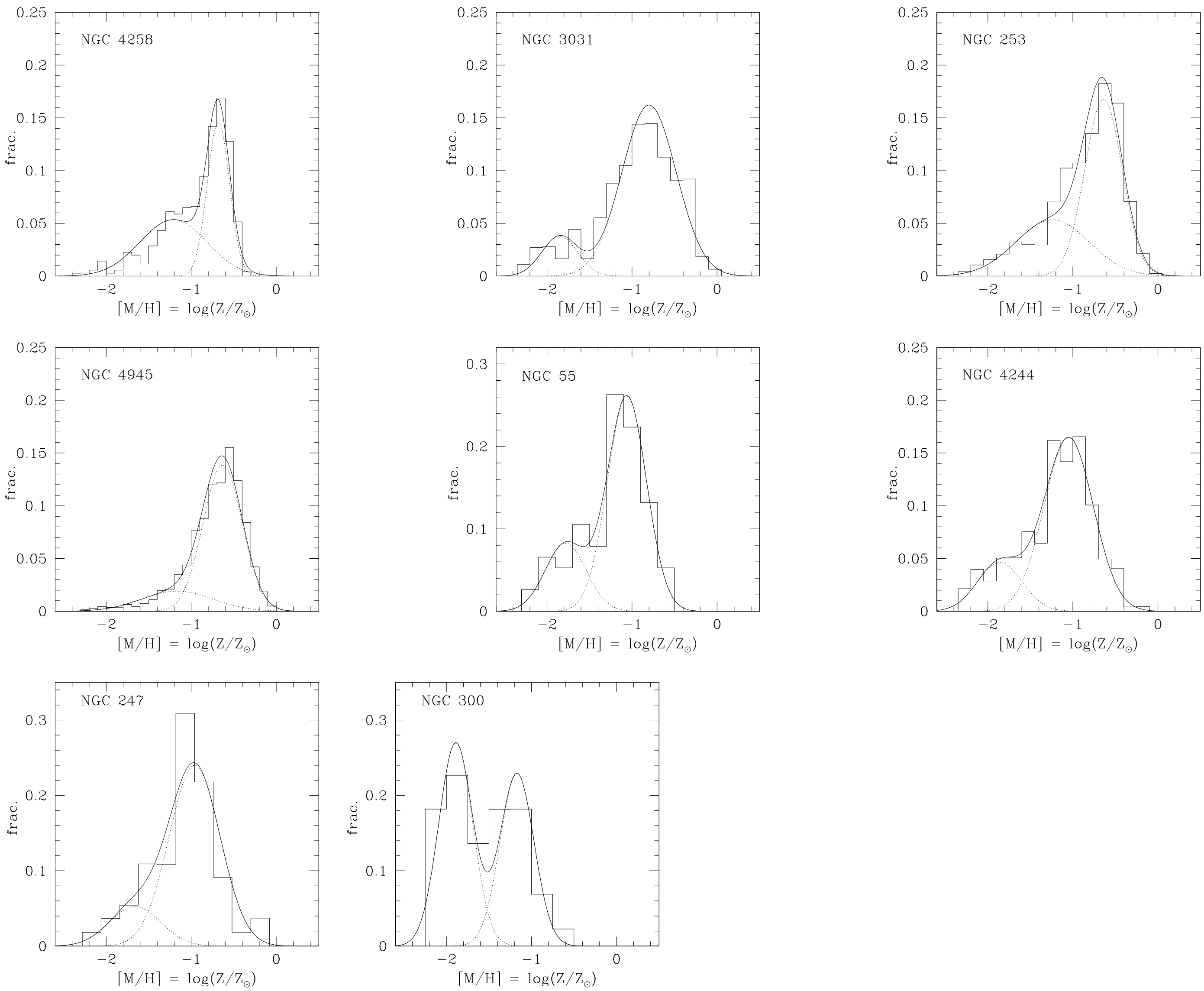

FIG. 1.— Metallicity distribution functions for the sample galaxies, with best fitting two Gaussian (dotted lines), and the combination of both. Each distribution has been normalized by the total number of stars. The histograms and the mixture models are plotted such that they both enclose the same area.

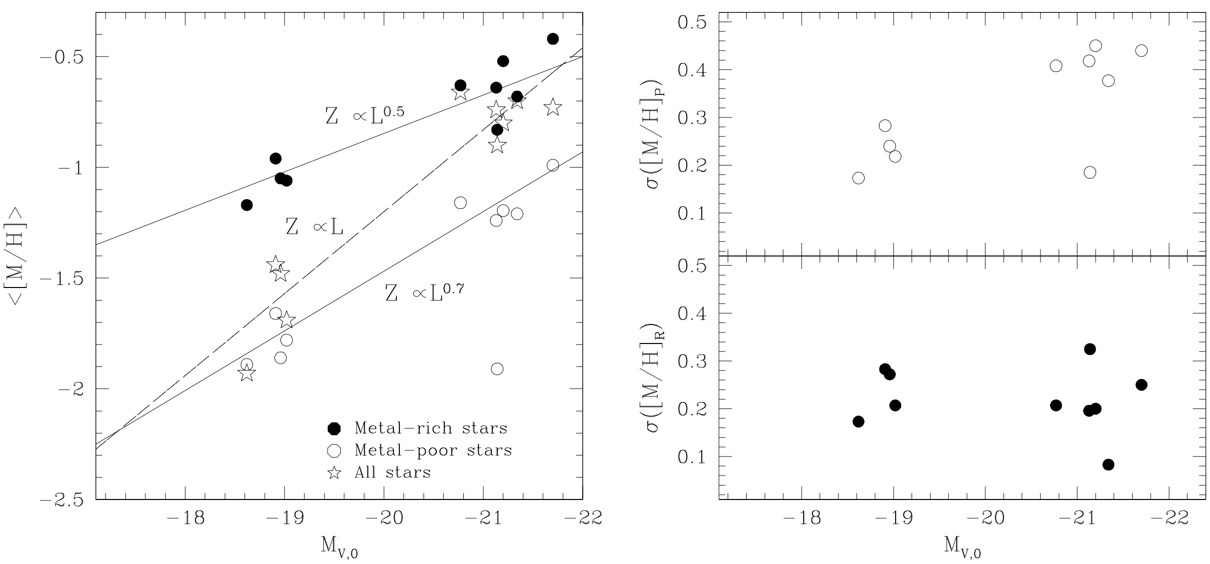

FIG. 2.— Left: The relationship between the mean metallicities of the metallicity distribution peaks as found by the KMM test, and the host galaxy luminosity. The filled dots show the mean metallicity of the metal-rich population, the circles show the mean metallicity of the metal-poor population. Open stars show the relationship between the mean stellar metallicity and the host galaxy luminosty. Right: Relationships between the metallicity dispersion of the metal-rich (bottom) and the metal-poor (top) stellar subpopulations and the host galaxy luminosity.